

Mapping the needs of Design for Maintenance in Electric Aviation

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Abstract

In the aviation industry, the issue of emission and pollution coupled with a concern over the availability and price of oil has led to a growing interest in the design and certification of electrically powered aircraft. Attention is nowadays paid to the technical feasibility of various aircraft design concepts and operational modes. However, there is still a gap in the knowledge of future maintenance operations associated with electric aircraft. The Dutch Electric Aviation Centre (DEAC) is currently researching the electric aircrafts using Cessna 337F Skymaster as a testbed at the Teuge International Airport (TIA). A brief overview of the electric propulsion system is made, and the possible maintenance challenges arising from the transition to electric aviation are identified. The design considerations from system engineering and analysis and the life cycle cost attribute that influence the maintainability evaluation and findings from the literature review, expert opinions, and study carried out at the DEAC are used to create a comprehensive mind-map of essential factors influencing maintenance performance of electric aviation.

Keywords: Electric Aviation; Aircraft maintenance; Design for Maintenance;

1. Introduction

The aviation industry is essential for the socio-economic development of many countries. Global energy consumption is greatly affected by the aviation industry, with a total energy consumption of 2.5% to 5% [1]. The main fuel being liquid fossil fuels that release various greenhouse gases, producing 2% of man-made carbon dioxide (CO₂) emissions, and this is expected to be 3% by 2050 [1, 2]. However, there is an observed growth of air transport despite the drawbacks. Besides the concern of emission and pollution, there is a growing concern about the availability and price of oil[3]. According to the European Union (EU) Commission vision, Flightpath 2050, aircrafts should reduce CO₂ emission by 75%, Nitrogen Oxide (NO_x) by 90%, and noise by 65% in reference to the emission scenario in 2000 [4]. As the aviation industry is expected to keep growing (after COVID-19) coupled with the environmental and commercial pressure, demands for environmental-friendly technology in terms of safety, air pollution, noise, and climate change have increased [1, 2].

This concern has led to a growing interest in the design and certification of electrically powered aircraft for thin-haul transport and urban air mobility as they offer better efficiency and have zero-emission (3, 5) locally. Many research projects are working on the new propulsion concepts in which

the battery is identified as the main critical parameter for the success of fully electric aircraft (FEA) and hybrid electric aircraft (HEA)[4]. The electric flight itself is not a new concept; there have been multiple attempts in the past to revolutionizing electric aircrafts such as Silentius in 1960, Hi-Fly in 1972, MB-E1 in 1973, and fully certified airframe HD-3 modified to carry batteries and electric motor. However, the success was hindered by the lack of high energy density batteries [3].

The main issue of adopting the electric propulsion unit in aviation is that aircraft is much more sensitive to mass. The travel range, coupled with increased mass and safety standards, poses a challenge to developing electric propulsion system concepts for aviation [3]. Much attention is paid to the technical feasibility of a wide variety of aircraft design concepts and operational modes. However, there is a gap in the knowledge of future maintenance issues associated with electric aircraft [5]. In comparison, an electric motor would require less maintenance than an internal combustion engine, but electric motors are not maintenance-free. Other factors to consider are thermal damages, vibrations, abrasion, voltage surges, and monitoring and replacement of high-speed bearings inside the motor core [5]. High-powered batteries and proposed electric aircraft configurations pose a new maintenance challenge and necessitate special training for the maintenance operators[5].

Currently, research is being carried out on the design and development of electric aircraft in the Netherlands by different organizations. The Dutch Electric Aviation Center (DEAC) is one of them. It is a knowledge center based on the Teuge International Airport (TIA) and focuses as a center of expertise on General Aviation (GA): flying, regulation, maintenance, and infrastructure modifications. The main goal of the DEAC is to stimulate flying on batteries or hydrogen. DEAC is using Cessna Skymaster 337F as a testbed. This aircraft piston twin engine in a so-called push-pull configuration, one pushing propeller in the rear of the fuselage and one tractor (pulling) in the nose of the aircraft. The linear configuration does not allow the aircraft to yaw towards the engine when the other engine fails, making it ideal as a testbed for electrification (see Fig. 1).



Fig. 1. Cessna 337F Skymaster (DEAC).

In this paper, an overview of the electric propulsion system is made based on which the possible maintenance challenges arising from the transition to electric aviation are studied. A comprehensive mapping of the need for Design for Maintenance (DfM) in electric aviation is made to help in the identification of essential factors influencing the maintenance performance of electric aviation. The comprehensive mind-map is based on the hybridization research being carried out at the DEAC.

2. Overview of electric propulsion system

Aircrafts are classified based on the degree of hybridization of their electric motor power and battery energy (see Table 1), the same method can be extended for other sources such as hydrogen. H_P is the ratio of the power of the electric motor to the total power required by the aircraft and H_E is the ratio of battery energy to the total energy required by the aircraft [6].

Table 1. Classification of electric propulsion architecture, adapted from [6]

Architecture	Degree of hybridization
Conventional	No electric power or energy used for propulsion (H_P & $H_E = 0$)
All electric	Electric power and energy used for propulsion (H_P & $H_E = 1$)
Hybrid electric	Mix of fuel and electrical energy and propulsive power ($H_P > 0$ & $0 < H_E < 1$)
Turboelectric	Fuel for energy storage and electric power transmission for propulsor(s) ($H_P > 0$ & $H_E = 0$)

2.1. Electric propulsion system

Electric propulsion systems differ in energy storage and conversions and are predominantly battery-based systems or fuel cell-based systems. In the case of battery systems, energy extraction takes place directly. However, the efficiency is limited by the chemical process during charging and discharging. Also, the system's mass does not change, except for air-breathing cells like Li-O₂ [3]. Fuel cells are silent with fewer vibrations and produce no NO_x emissions during the operations. There are different types of fuel cells, but for aviation applications, Proton Exchange Membrane Fuel Cell (PEMFC), which operates at low temperatures, and Solid Oxide Fuel Cell (SOFC), which operates at high temperatures, are mainly considered [1]. PEMFC coupled with lithium battery to meet peak take-off, and climbing load can be seen in HY4, a fuel cell-powered four-seat passenger aircraft developed by DLR German aerospace centre [1].

Key components of an electric propulsion system are the electric motor, energy storage systems, inverter, and isolation monitoring. The use of electric motors may reduce the maintenance cost compared with turbine or piston engines. Still, the quantitative study concluded that there is uncertainty in maintenance cost, and it should be an acceptable risk [7]. An overview of the fuel possibilities can be found in Table 2.

Table 2. Overview of fuel possibilities, adapted from [3]

Energy source	Summary
H ₂ (Gas)	Requires high-pressure tanks. Tanks are heavier than actual fuel and pose safety issues

H ₂ (Liquid)	Requires cryogenic tanks. Tanks are heavier than actual fuel and pose safety issues
Battery	Requires casing with temperature cooling system
Fuel cell	Same issues as storage of hydrogen and require additional parts such as pump, water supply, etc.

3. Maintenance challenges

Aircraft systems and components are bound to deteriorate over the life cycle, so maintenance needs to be performed to ensure flight safety, airworthiness, and aircraft reliability. The aircraft consists of mainly three categories: the engine, the airframe, and avionics. In a study [8], it is argued that the majority of the hazards to which FEA is exposed is similar to aircraft with the conventional propulsion system and that it is possible to mitigate them under the current regulatory paradigm. However, the very concept of FEA implies a significant departure from the current paradigm of design, certification, and operations [8].

In a study [8], safety and certification considerations for FEA/HEA were investigated where the developing electric aircraft architectures were categorized, and key hazards associated with each configuration were discussed. There are concerns over the high voltage work environment being fatal to maintenance operators, especially during the maintenance and replacement activities. This concern was also addressed in the study [5], in which a qualitative analysis was performed by interviewing maintenance operators over the introduction of electric aircraft. The Li-ion batteries pose a risk of bursting into a self-sustaining fire and releasing toxic fumes and interference of different batteries such as Li-ion and NiCad. The fumes released by NiCad batteries tend to neutralize Li-ion batteries when a certain maintenance procedure is performed.

The gradual shift towards FEA has a more significant impact on the airport infrastructure requirements and operational compatibility. According to the International Civil Aviation Organization (ICAO) design manual, the airport infrastructure depends on 13 aircraft characteristics: design, wingspan, main gear wheel span, mass, length, nose wheel angle, turning radius, blast production, required runway distance, turnaround time, amount of traffic, power demand, and fuel demand. These factors need to be reflected in the hangar design to achieve an optimal maintenance process. As per the regulations laid out by EASA Part-145, the maintenance organization must comply with the requirements of the aircraft on

which it performs maintenance. When a new type or variant of aircraft is introduced, the maintenance organisation must have appropriate facilities, tools & equipment, and workforce. Hangars, vertiports, and maintenance facilities will need to follow the OSHA standards for electrical safety. From the capacity point of view, additional storage of the batteries has to be considered [5, 9].

Along with technical and maintenance challenges, the uncertainty introduced by electric aircraft is regulatory uncertainty. This involves safety regulations, environmental regulations, maintenance regulations, etc., in the context of necessary licenses to construct and operate the aircraft under appropriate regulatory authority [10]. If it is not taken into account at an early design phase, it could lead to the premature retirement of the aircraft [10]. EASA Part-66 focuses on the maintenance personnel, from the training to licensing the Aircraft Maintenance Technicians (AMT). However, there are no specific requirements regarding the aircraft with an electric propulsion system.

Technological advancements in avionics and air traffic management systems have triggered enhanced connectivity and integration of airborne systems, ground systems, and other stakeholders. This connection enables an increase in efficiency and safety. Still, at the same time, it poses new challenges in maintaining the Cyber-Physical System (CPS) and security on all levels of the system, not only front-facing information technology (IT) systems but also operational technology. There is a knowledge gap among the maintenance personnel arising due to the integration of IT-OT. Unlike the physical component, which is straightforward, the maintenance of the CPS is cumbersome but critical.

In the study [5], it was recommended to ensure proper training and certification of maintenance operators to prepare for the emergence of electric aircraft. The participants of the study [5] emphasized that the lack of safety training to maintain high-powered electrical hardware should motivate designers to focus on the design for maintainability, especially modularity and maintenance-related standards.

4. Mapping the needs for maintenance in electric aviation

In the case of aircraft design, there are aeronautical, electrical, electronics, mechanical, industrial, safety, and maintenance engineers working together in synergy to achieve an optimal and efficient design, to achieve this, also considering cost-effectiveness as an important aspect, the system engineering process is a suitable approach [11]. There are a variety of design-to-requirements based

on the system characteristics that must be considered when developing a design criteria that includes design, manufacturing, safety, human factor, environment, and financial aspects [11]. In the case of electric aviation, It is important to emphasize the maintenance of not only the aircraft system but also the airport ecosystem. As electric aviation is relatively a new field, it is necessary to incorporate the safety and training aspects in the early design phase. These requirements can either be mutually supportive or conflicting and require a trade-off study to achieve design optimization [12].

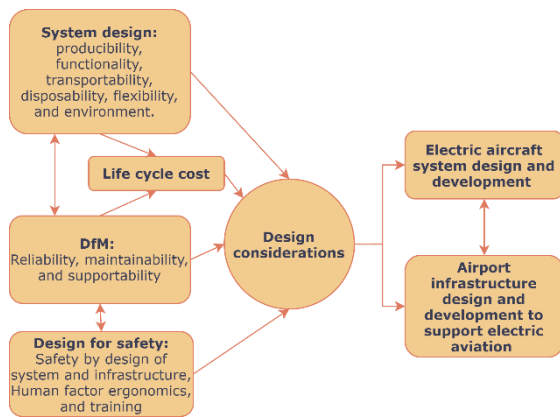


Fig.2. Design consideration for electric aviation, inspired by [11]

DfM plays a vital role in the early design phase of a product and influences how easily and efficiently it can be maintained to keep the product in good and working condition [13]. For any system, it is desirable to maximize the system's availability while keeping the total life cycle costs low, where availability is greatly influenced by the maintainability, reliability, and supportability of the system [13]. A set of guidelines was developed to provide DfM ideas [13]. It is useful to achieve an optimized product design that facilitates maintenance activities during its life cycle, and it can be incorporated easily without changing the design procedure. Among these, maintainability is one of the most critical system design parameters that affect the ease of maintenance [14]. System failure is inevitable despite emphasizing the reliability factor, so the ability to restore it is crucial [14].

In a study [15], the life-cycle design attributes for maintainability evaluation were classified into inherent attributes and external factors. Inherent attributes are considered during the design and manufacturing process that have a greater influence on the system's maintainability. The external factors are associated with the usage of the system, such as installation, working environment, and maintenance strategies [16].

Modifying existing aircraft to support electric propulsion systems and fuel cells encompasses a complete rethinking and re-design to facilitate safe and efficient interaction with both aircraft system components and the airport ecosystems, storage facility, and maintenance organization. As maintenance operations deeply affect both operability and the financial side of an asset during all the lifetime, the DfM approach is being considered from an early stage in parallel to the development of the system itself.

4.1. Mind map

For the successful adoption of electric aviation and community acceptance, it is essential to focus on the technical feasibility and the safety and life cycle cost. Based on the identified maintenance consideration associated with the introduction of electric aviation, the design-to-requirements from system engineering and analysis [11] were categorized into system design, life cycle cost, DfM, and design for safety (see Fig. 2). The design considerations influence both aircraft system design and the airport infrastructure. For electric aviation, life cycle cost attributes based on the frame chart for the maintainability evaluation system [15] can be categorized into DfM, supporting infrastructure, maintenance, the technical level of both operators and maintenance personnel. As maintainability is already a part of DfM, life cycle cost attributes correlate to the design-to-requirements. The design process must follow the regulations set by the aviation regulatory bodies, and they must be included in the early design phase. Using this correlation and findings from the literature review, expert opinions and study being carried out at the DEAC, a comprehensive mind-map of essential factors influencing maintenance performance of electric aviation is created (see Fig. 3), where the design considerations that have an impact on the maintenance of the electric aviation has been further explained.

The mind map is mainly divided into the following categories:

- Maintenance of electric aircraft
- Supporting infrastructure for maintenance
- Training of maintenance
- Maintenance certification
- Maintenance of IT-OT

The aircraft's initial design will affect the performance and maintenance at the later stages of the life cycle, so it is important to compare conventional aircraft with electric aircraft and understand the system components that are going to be affected by the transition into electric propulsion

system. Identification of failure modes and system mechanisms is effective in understanding the critical components that may require frequent maintenance. As the aircraft is being retrofitted with lighter components to compensate for the lower energy density of the batteries, structural health monitoring and predictive maintenance could be promising during the operational stage. Suitable maintainability, reliability, and supportability guidelines can be incorporated into the detailed design of the airframe, components, and avionics. The DfM solutions created must be tested before implementation, this can be done using the test-bed or digital mock-up (DMU). Appropriate maintenance strategies need to be formulated and implemented through the Computerized Maintenance Management System (CMMS). It is crucial to collect maintainability and reliability data during the testing and operational phase to access and optimize life cycle costs. As aviation is one of the most regulated industries, it is critical to reflect on the regulations set by aviation regulatory authorities at every development step. This sets the boundary conditions for the design process. Integration of supply chain logistics into maintenance and operations plays a significant role.

Maintenance of IT-OT focuses on the software systems, cyber security, configuration management, and collection, storage, and analysis of the data. Configuration management is important to ensure a smooth integration when a new component is introduced into an existing system.

The safety aspect of electric aircraft is governed by both its initial design and maintenance policies

employed during the operational stage. Maintenance tasks, if not done right, could have severe consequences of the system safety. This could be improperly done maintenance tasks or inducing failure by performing tasks on a different system component. It is important to perform a rigorous safety assessment at the early design stage and incorporate safety by design process to ensure the safety of both system and maintenance operators working on the system. This also encompasses the focus on the human factor ergonomics, as it plays an important role in the maintenance operators' mental and physical health and human-oriented productivity management.

The supporting infrastructure, especially hangars, tools, and equipment, greatly influences maintenance and safety. For the time being, the hangars need to accommodate both conventional and electric aircraft; this may lead to some challenges, as seen in the handling of Li-ion and NiCad batteries. The DfM for the workshop and the ground equipment communicating with the aircraft must be considered at an early design phase to ensure ease of maintenance and safety. Also, handling and maintenance of charging infrastructure to have an optimized turnaround of aircraft and ground vehicles supporting the operations and maintenance process must be taken into considerations.

There is a lot of concern over handling high voltage equipment in electric aircraft; this raises concerns over the safety and training aspects. Even though the design for maintainability encompasses human factor ergonomics and safety, it must be

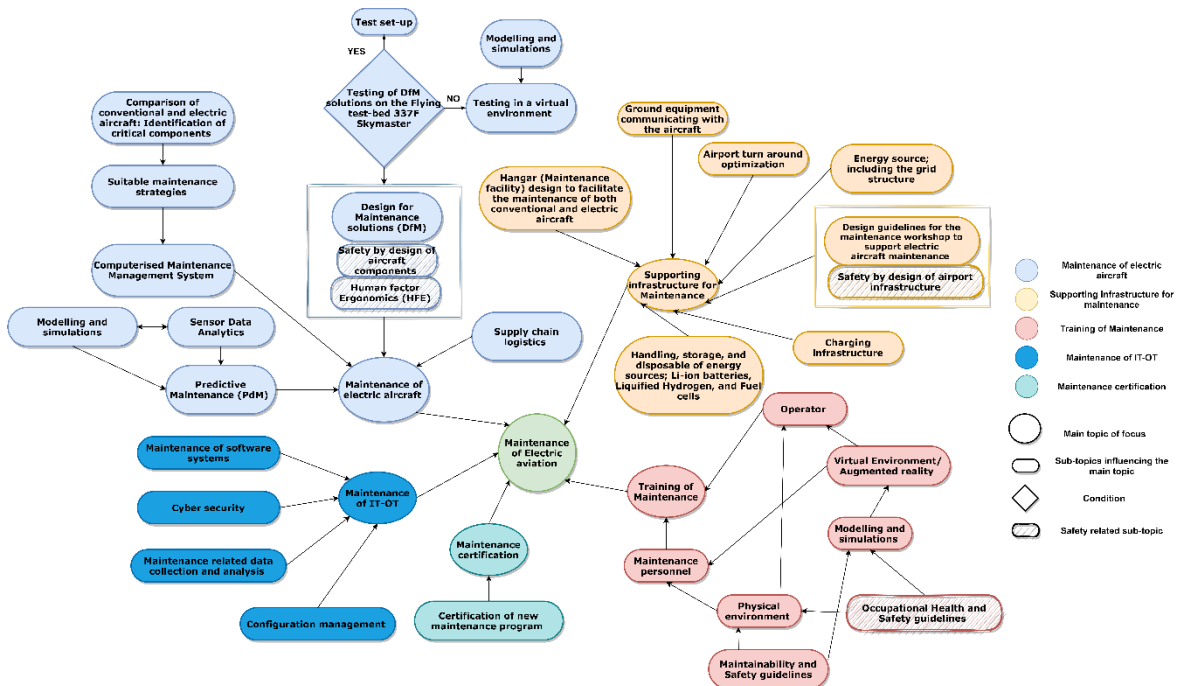


Fig. 3. Mapping of the need for DfM in electric aviation

investigated on a component level, and system safety design must be incorporated. It is suggested to encourage the involvement of the maintenance personnel in the early design phase. Along with maintenance personnel, operators must be aware of basic maintenance in case of an emergency. During the design phase, it is efficient to use virtual reality and augmented reality for training operations.

The proposed mind-map can be used to create a framework to decide on the DfM solutions. It is important to identify the key performance indicators based on the design requirements and use them to validate the framework. DMUs can be used to simulate different scenarios and collect the data, the simulation data can then be used to interpret parameters such as maintenance time, safety indicator, or workspace ratio.

5. Conclusion

The growing concern over emission-led pollution and climate change have led to an increase in the research and development of electric aircraft. However, a lot of attention is paid to the aircraft's technical feasibility and conceptual design, and there is a knowledge gap when it comes to the future maintenance of electric aircraft.

The paper aimed to have a higher-level overview of electric aircraft and understand the possible maintenance challenges arising from the transition to electric aviation. Challenges such as handling and maintenance of high-powered batteries, lack of understanding of configurations of the aircraft propulsion system, key hazards associated with fixed-wing electric aircraft, and regulatory uncertainty were identified. DfM approach is ideal at the early design phase, and it also has influences over the the airport infrastructure design

Based on (a) the design considerations from the system engineering and analysis, (b) life cycle cost attributes, (c) findings from the literature review, expert opinions, and (d) study undertaken at the DEAC, a comprehensive mind-map of essential factors influencing maintenance performance of electric aviation is created. The factors influencing the operational capabilities, total life cycle cost, and safety are categorized: maintenance of electric aircraft, maintenance certification, maintenance of IT-OT, supporting infrastructure for maintenance, and training of maintenance.

From the maintenance perspective, future research should focus on creating a maintenance decision-making framework based on the mind-map that can enable the designer to make a trade-off and

achieve optimal DfM solutions. As there is not enough quantitative data available and uncertainty in maintenance cost, maintainability and reliability data must be collected and analyzed to improve the design further.

Acknowledgement

The authors would like to acknowledge the financial contribution and support provided by the DEAC, Gemeente Apeldoorn and the University of Twente.

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